

Gas Accretion as the Dominant Formation Mode in Massive Galaxies from the GOODS NICMOS Survey

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ABSTRACT

The ability to resolve all processes which drive galaxy formation is one of the most fundamental goals in extragalactic astronomy. While star formation rates and the merger history are now being measured with increasingly high certainty, the role of gas accretion from the intergalactic medium in triggering star formation still remains largely unknown. We present in this paper indirect evidence for the accretion of gas into massive galaxies with $M_* > 10^{11} M_\odot$ at redshifts $1.5 < z < 3$ using results from the GOODS NICMOS Survey (GNS). Our method utilises the observed star formation rates of these massive galaxies based on UV and far-infrared observations, and the amount of stellar and gas mass added due to observed major and minor mergers to calculate the evolution of stellar mass in these systems. We show that the measured gas mass fractions are inconsistent with the observed star formation history for the same galaxy population. We further demonstrate that this additional gas mass cannot be accounted for by cold gas delivered through minor and major mergers. We argue that to sustain star formation at the observed rates there must be additional methods for increasing the cold gas mass, and that the likeliest method for establishing this supply of gas is by accretion from the intergalactic medium. We calculate that the average gas mass accretion rate into these massive galaxies, which is later turned into stars between $1.5 < z < 3.0$, is $\dot{M} = 83 \pm 36 M_\odot \text{ yr}^{-1}$. This is similar to what is predicted in detailed simulations of galaxy formation. We show that during this epoch, and for these very massive galaxies, $61 \pm 21\%$ of stellar assembly is a result of gas accretion, while the remaining $\sim 39\%$ is put into place through mergers. This reveals that for the most massive galaxies at $1.5 < z < 3$ gas accretion is the dominant method for instigating galaxy formation.

1 INTRODUCTION

Both observations and theoretical models now overwhelmingly suggest that galaxies in the universe have evolved from an early galaxy population dominated by lower mass systems undergoing significant star formation in the early universe, to the large and relatively passive galaxies that we find today (e.g., Conselice 2006; Bouwens et al. 2010). How this transformation occurs, that is how we get from young low mass galaxies to the large massive galaxies we see in today's universe, is a highly debated topic. Essentially, we want to answer the question - how do galaxies assemble their stellar masses? The answer to this question will have profound implications for both the physics of galaxy formation and for understanding properties of the universe itself.

Historically, it was once thought that galaxies formed in a manner similar to stars through a collapse of gas that later, through some process, underwent intense star formation. In this paradigm the total baryonic mass of a galaxy does not change significantly with time, and its stellar mass evolves by rapidly converting gas into stars. However, it is clear that

galaxies must form in a hierarchical way through mergers and accretion of material from the intergalactic medium. This view has supporting evidence from both observations of the stellar mass functions of galaxies (e.g., Bundy et al. 2006; Mortlock et al. 2011), direct observations of mergers in the distant universe (e.g., Conselice et al. 2003, 2008; Bluck et al. 2009, 2012), as well as through the evolution of galaxy sizes (e.g., Ferguson et al. 2004; Trujillo et al. 2007; Buitrago et al. 2008). Evidence from internal kinematics also suggests that galaxy formation is driven at least in part by the accumulation of gas from the intergalactic medium falling onto a galaxy (e.g., Keres et al. 2005; Genzel et al. 2008; Dekel et al. 2009; Bournaud et al. 2011).

While it is now generally accepted that galaxy formation is a hierarchical process driven by the accumulation of stars and gas located outside of a galaxy after its initial formation, the details of this assembly remain largely unknown. Cold gas infall into galaxies, otherwise known as ‘cold gas accretion’ is theorised to be an important aspect in the process of massive galaxy formation (e.g., White & Frenk

1991; Birnboim & Dekel 2003; Keres et al. 2005; Dekel et al. 2009), and even perhaps the dominant method by which galaxies assemble their mass. However, there is little to no evidence for gas accretion onto galaxies at high redshift currently (e.g., Steidel et al. 2010), although some claims are appearing at lower redshifts (e.g., Rauch et al. 2011). This is primarily due to the difficulty of observing this process since the covering fraction of accreting cold gas is likely not high (e.g., Dekel et al. 2009), nor would this gas be easily detected in, for example, absorption (e.g., Weiner et al. 2009; Giavalisco et al. 2011).

In this paper we develop a new approach to this problem by analyzing the evolution of the massive galaxy population in terms of the history of its baryonic assembly. We examine how the stellar mass of a galaxy is built up over time through various galaxy formation processes that can be observed within a unique sample of $M_* > 10^{11} M_\odot$ galaxies at $1.5 < z < 3$ taken from the GOODS NICMOS Survey (GNS) (Conselice et al. 2011). By examining the addition of stellar mass due to major and minor mergers (Bluck et al. 2009; 2012), and the observed star formation history (Bauer et al. 2011) we provide through this method circumstantial evidence for gas inflow, or gas imported in through extremely minor mergers, as an important process in galaxy assembly.

After comparing the amount of accreted mass to the mass assembled through merging, we conclude that gas accretion is likely the dominant process for massive galaxy assembly at this epoch. We further discuss the comparison with theory, and describe some of the implications of our results, including how our work relates to the G-dwarf problem (e.g., Larson 1974) the rapid gas depletion time-scales in galaxies.

This paper is organised as follows: §2 includes a discussion of the data sources we use in this paper, and the sample selection, §3 is a description of our baryonic mass assembly analysis, §4 presents our arguments for gas accretion and §5 is our summary. We use a standard cosmology of $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, and $\Omega_m = 1 - \Omega_\lambda = 0.3$ throughout.

2 DATA

The data and methods we use in this paper originate from the GOODS NICMOS Survey (GNS), and are described in detail in Conselice et al. (2011), Mortlock et al. (2011), Bluck et al. (2009, 2012) and Bauer et al. (2011). The primary galaxies we examine are 81 massive galaxies with stellar masses $M_* > 10^{11} M_\odot$ at redshifts $1.5 < z < 3$. These were selected through a variety of colour selections, include Distant Red Galaxies (DRGs), IRAC Extremely Red Objects (IEROs) and the BzK galaxies (Conselice et al. 2011). We also utilise photometric redshifts which are described in detail in Grützbauch et al. (2011a,b).

To calculate stellar masses we use a Bayesian method to fit spectral energy distributions based on various star formation models to the galaxy photometry. The distribution of the resulting stellar masses gives us an error in their measurement, and we take the peak value of the distribution as a measure of our stellar mass. A Salpeter IMF was used in these calculations. Further details about our sample selected are included in Conselice et al. (2011) where we refer interested readers for more details.

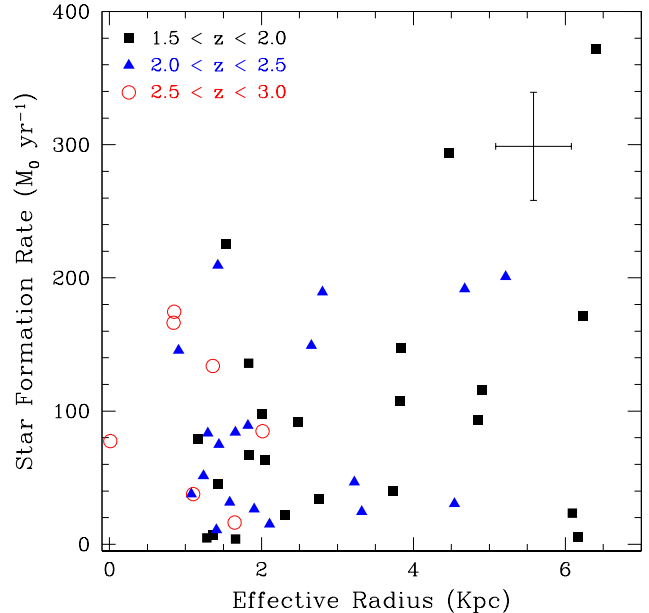


Figure 1. The relationship between the star formation rate and effective radius, R_e , divided into three redshift ranges between $1.5 < z < 3$ for galaxies with stellar masses $M_* > 10^{11} M_\odot$.

The galaxy effective radii which we use in this study to measure star formation rate densities, originate from GALFIT fits to our NICMOS imaging, taken from the methods and catalog of Buitrago et al. (2008, 2011). These are single Sérsic profile fits to the light profile in which we retrieve both a Sérsic index, n , as well as the effective radius, R_e . These sizes are measured solely using the GOODS NICMOS Survey H_{160} -band imaging. Detailed simulations show that we are able to retrieve these parameters given the observing conditions of our sample (Buitrago et al. 2011).

We also utilise results from previously published GNS studies which describe the evolution of this sample in terms of the star formation rate (Bauer et al. 2011) and the merger history (Bluck et al. 2009; 2012) as a function of stellar mass. We give brief summaries of these analyses in reference to our current study throughout this paper. The star formation rates we use for our galaxies are measured through rest-frame UV and Spitzer $24 \mu\text{m}$ measurements. For the UV star formation rates which we use for most of the analysis here, we utilise ACS z-band imaging to obtain a rest-frame UV flux measurement which is converted to a star formation rate after applying a k-correction (Bauer et al. 2011). We further measure the UV slope for each galaxy using the UV colour to correct for dust extinction.

Our galaxy sample is chosen simply as all systems within our sample which have stellar masses of $M_* > 10^{11} M_\odot$, and are at redshifts $1.5 < z < 3$. We do not select certain types of galaxies within this selection, such as passive galaxies or star forming galaxies. Although amongst this sample less than 5% are passive galaxies (Bauer et al. 2011),

we include all of the galaxies in this selection as the star formation rate and gas mass fractions we use are an average within our stellar mass selection. We assume that our sample of galaxies represents different phases of a massive galaxy's life-span throughout the redshifts $1.5 < z < 3$ – for example, the fraction of galaxies which are passive represents the fraction of time a typical galaxy in our sample is not undergoing star formation. Our sample of galaxies all have very similar stellar masses and environments, suggesting that these systems should have very similar formation histories (e.g., Grützbauch et al. 2011a,b). The result of this is that we can obtain the average amount of stellar mass added to this sample selection due to star formation and merging without having to worry about biases from different evolutionary phases.

This selection also limits our ability to trace the exact same galaxies over redshifts due to the fact that galaxies are growing in stellar mass due to merging and star formation, and thus there will be more galaxies in our stellar mass limit towards lower parts of the redshift selection. In Conselice et al. (2011) and Mortlock et al. (2011) we discuss the stellar mass evolution for our sample. By examining our mass selection used in this paper we find that the number density of galaxies selected by the criterion $M_* > 10^{11} M_\odot$ grows by a factor of between two and four from redshifts $z = 3$ to $z = 1.5$. We examine later in this paper how our selection would change if we examine a massive galaxy sample at a constant co-moving volume (e.g., Papovich et al. 2011).

Figure 1 shows a summary plot of our data and massive galaxy sample. Plotted are the star formation rates vs. the effective radii for each galaxy in our sample, divided into different redshift bins. The average star formation rate for our sample is roughly constant with redshift (Bauer et al. 2011), and there is a slight evolution in the sizes of these galaxies, such that they are growing with time (e.g., Buitrago et al. 2008).

3 EVOLUTION OF GALAXY MASS

3.1 Galaxy Gaseous Mass at $z > 1.5$

The evolution of the cold gas mass within galaxies is an important aspect for understanding galaxy evolution, yet our observations of this quantity are still very basic and are prone to systematic errors. Furthermore, all of these measurements are indirect, even when using CO as a proxy. We present in this section arguments for how to quantify gas masses in our galaxy sample based on the inverse Schmidt-Kennicutt relation (e.g., Kennicutt 1998; Erb et al. 2006; Daddi et al. 2010; Boquien et al. 2011) using our measured SFRs and sizes (Bauer et al. 2011, Buitrago et al. 2011; §2).

Obtaining a measure of the cold gas mass in galaxies is challenging, and there are several attempts to measure this at high redshift (e.g., Erb et al. 2006; Mannucci et al. 2009; Daddi et al. 2010), yet these methods contain several important limitations which must be considered. These inferred cold gas mass fractions are measured through the inverse Schmidt-Kennicutt relation, which relates the cold gas mass density to the star formation rate density (e.g., Kennicutt 1998). This relation, for nearby galaxies, has been studied in detail in recent papers such as Bigiel et al. (2011)

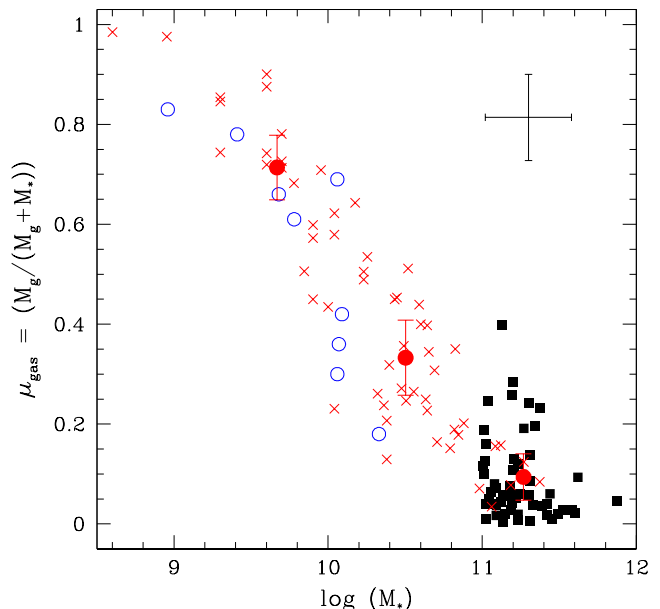


Figure 2. The relationship between stellar mass (M_*) and the gas mass fraction μ_{gas} , which is the ratio of the cold gas mass divided by the stellar+gas mass. The red crosses are for $z > 2$ galaxies from Erb et al. (2006) and the blue circles are from Mannucci et al. (2009). The solid boxes are from the GNS (this work). The error bars show the averages and the 1σ dispersion as a function of stellar mass.

who find a significant scatter, but still a correlation, between these two quantities using molecular gas and star formation measurements. Much of this scatter is however proposed by Krumholz et al. (2012) to be due to observational projection effects, and that there is a universal star formation-gas density law that applies at all redshifts (see also Narayanan et al. 2011). There is also evidence that at least two star formation laws may apply at higher redshifts, one for disk-like galaxies, and another for starbursts (e.g., Bouche et al. 2007; Daddi et al. 2010; Genzel et al. 2010).

Most high- z observations, including ones based on CO detections, argue that the cold gas mass fraction, M_g/M_* is between 10-50% for galaxies more massive than $M_* = 10^{10} M_\odot$ (e.g., Genzel et al. 2010; Daddi et al. 2010; Figure 2). This cold gas mass fraction tends to rise for lower mass galaxies (e.g., Erb et al. 2006; Mannucci et al. 2009). There is also evidence that the efficiency of star formation within starbursts, such as ULIRGs and sub-mm galaxies is more efficient than that given by the standard Schmidt-Kennicutt law, resulting in lower derived gas mass fractions at a measured star formation rate density (e.g., Daddi et al. 2010; Boquien et al. 2011).

We calculate gas masses for the massive $M_* > 10^{11} M_\odot$ sample, and derive the cold gas mass fraction using a form of the global Schmidt-Kennicutt law calibrated for nearby star forming galaxies. The relation we use is:

$$\Sigma_{\text{SFR}} = (2.5 \pm 0.7) \times 10^{-4} \left(\frac{\Sigma_{\text{gas}}}{1 M_\odot \text{pc}^{-2}} \right)^{1.4 \pm 0.15} M_\odot \text{yr}^{-1} \text{kpc}^{-2}, (1)$$

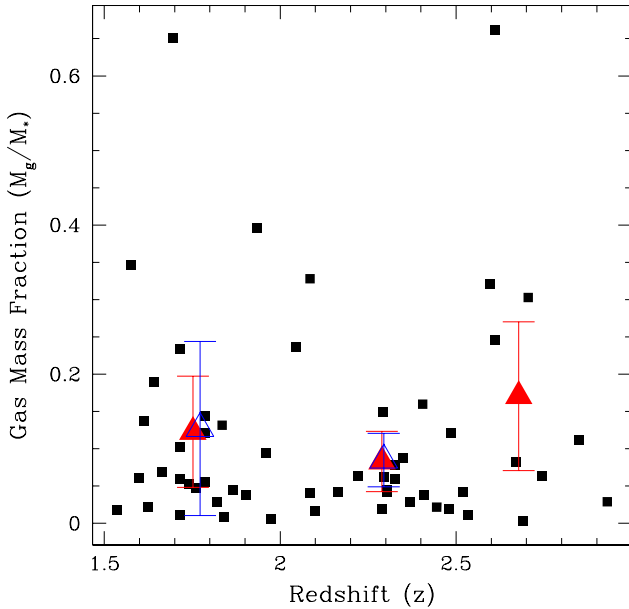


Figure 3. The relationship between the gas mass fraction and redshift for galaxies with stellar masses $M_* > 10^{11} M_\odot$. The error bars show the 1σ scatter for the average values which are plotted as large solid triangles. The red triangles are for this method when examining galaxies at a stellar mass cut off of $\log M_* > 11$, and the open blue triangles are when holding at a constant co-moving volume to account for more galaxies entering our mass selection over time.

where Σ_{SFR} is the surface density of star formation, and Σ_{gas} is the surface density of cold gas. We assume in this calculation that the star formation follows the distribution of H-band light, which is found to be the case (Ownsworth et al. 2012 in prep). We calculate the star formation rate density within each galaxy based on the effective radius, R_e (§2), and half of the measured total star formation rate. From this we obtain the gas mass density using eq. (1) and we then calculate the total gas masses in our systems based on this.

In Figure 2 we plot the gas mass divided by total baryonic mass ($M_* + M_g$) for our sample massive galaxies. We also show in Figure 2 comparison values from Erb et al. (2006) who study galaxies at similar redshifts, but at lower masses, and Mannucci et al. (2009) who study similar star forming galaxies at $z > 2$. Figure 2 shows that the galaxies in our sample, as shown by the black boxes, have gas total mass fractions which are around 10%, with some scatter. However, our values are lower than the gas total mass fraction found for lower stellar mass systems, and extend the trend found in Erb et al. (2006) and Mannucci et al. (2009), such that the highest mass systems have the lowest relative gas fractions.

To determine how much more stellar mass these galaxies could acquire from the existing cold gas in star formation events, we show in Figure 3 the gas mass fraction defined as the cold gas mass divided by the total stellar mass. The averages at the three redshift ranges and their 1σ dispersions are at $z \sim 1.75$ - $f_g = 0.13$, $\sigma = 0.15$, $z \sim 2.29$ - $f_g = 0.08$, $\sigma = 0.08$ and at $z \sim 2.68$ - $f_g = 0.17$, $\sigma = 0.19$.

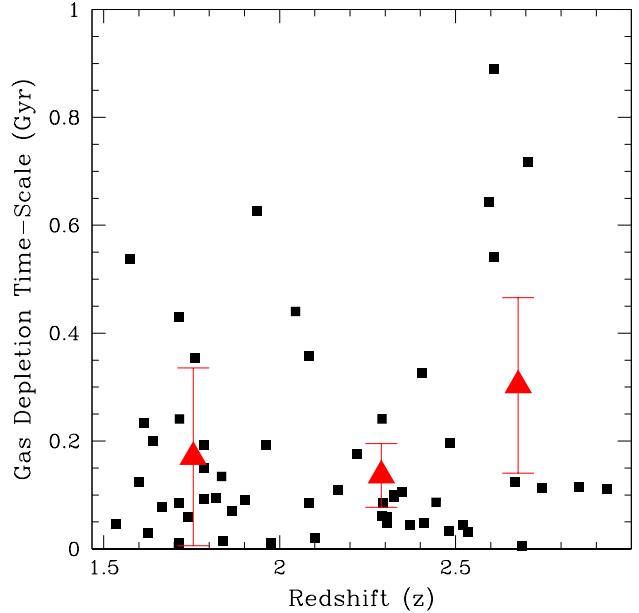


Figure 4. The gas depletion time scale shown as a function of redshift for each galaxy within our sample. The time-scale is in Gyr, and the triangles show the average values at different redshift ranges, and the errors bars are the 1σ scatter.

We also show these averages if we hold our selection at a constant co-moving volume as the open blue triangles. We thus find, as others have, that the gas mass density is roughly constant with redshift, as is also found by comparing derivations of gas mass fractions at different redshifts for lower mass galaxies (e.g., Erb et al. 2006; Mannucci et al. 2009). Furthermore, these average values not only have a large dispersion, but also contain potential systematics which we examine later. We find very similar gas mass fractions when we follow a constant number density of galaxies from high to low redshift within $1.5 < z < 3$. This is the result of the gas mass fractions being largely similar when using a $M_* > 10^{11} M_\odot$ selection, or when using a constant number density selection, as used in e.g., Papovich et al. (2011). This is due to the fact that the constant number density selection is always within the $M_* > 10^{11} M_\odot$ selection, and within this mass selection the values of the gas mass fraction are uniform on average.

It has been noted in previous studies that the gas masses observed are not high enough to account for the prolonged star formation in these systems (e.g., Genzel et al. 2009). Figure 4 displays the depletion time-scale, the gas mass divided by the star formation rate (ψ), i.e., M_g/ψ – showing that nearly all galaxies in our sample would be depleted of gas in less than 0.5 Gyr assuming 100% efficiency of star formation. This is much less than the time within the redshift interval we examine in this paper. This suggests that something is replenishing the gas within these massive galaxies over time.

3.2 The Evolution of Stellar Mass

Galaxy stellar mass is a measure of both the amount of gas which has been converted into stars over time, as well as the amount of mass which has been accreted into the galaxy from previously existing galaxies. We are able to trace both of these properties for the most massive galaxies in the universe up to $z \sim 3$ (e.g., Conselice et al. 2011; Mortlock et al. 2011; Bauer et al. 2011; Bluck et al. 2012).

The reason we can do this now is that we have constructed a complete sample of massive galaxies at redshifts $z = 1.5$ to $z = 3$ which have stellar masses in excess of $M_* = 10^{11} M_\odot$ (Conselice et al. 2011). By examining galaxies at such a high mass limit we are ensuring to some degree that we are examining similar galaxies at different redshifts, given that very few galaxies have masses much higher than this. Although some galaxies just below the $M_* = 10^{11} M_\odot$ border at the high end of our redshift range will spill over into it during the interval $1.5 < z < 3$, the properties of these slightly lower mass systems are similar to those at $M_* > 10^{11} M_\odot$ (Conselice et al. 2011). Furthermore, all of the quantities we discuss in this paper are averages, rather than integrated or total properties, which limits the effect of having new galaxies appear in the selection.

In previous work, we carried out detailed calculations of the merger and star formation histories for a sample of 81 massive galaxies at $1.5 < z < 3$ (Bauer et al. 2011; Bluck et al. 2012) which we discuss here. We find that the average star formation rate for galaxies with stellar mass, $M_* > 10^{11} M_\odot$ is $\langle \psi \rangle = 103 \pm 8 M_\odot \text{ yr}^{-1}$ (Bauer et al. 2011), with a dispersion of $75 M_\odot \text{ yr}^{-1}$. We find very similar star formation rates for the same sample when we examine their *Herschel* far-infrared spectral energy distributions (Hilton et al. 2012 submitted).

The observations we use in this paper are measured from redshifts $z = 3$ to $z = 1.5$. This time period is roughly 2.16 Gyrs. We calculate how much stellar mass is created during this redshift interval by simply integrating the star formation rate. When we do this, we obtain the average amount of stellar mass created per galaxy over this redshift interval, the value of which is: $\langle \psi \rangle \delta t \sim (2.2 \pm 0.2) \times 10^{11} M_\odot$. This is roughly the average amount of stellar mass originally in our sample of galaxies at our highest redshift, $z \sim 3$, which we denote as $M_*(t=0) = M_*(0)$. Thus we can measure the ratio of the stellar mass created in star formation within these galaxies divided by the original stellar mass within these systems, or $\langle \psi \rangle \delta t / M_*(0) = 1.1 \pm 0.13$. We do not consider directly here the amount of matter brought back into the interstellar medium of these galaxies due to SN and other stellar evolutionary events. The amount of this is less than 5% of the stellar mass created (e.g., Papovich et al. 2011), and is much lower than our systematic errors. In any case, it is the possibility that this gas is reused in star formation that has implications for our results, rather than the removal of stellar mass.

When considering the accretion of stellar mass into our sample of galaxies, we also have to consider both major and minor mergers, as another important route for obtaining stellar mass. The amount of stellar mass added to a galaxy due to the merger process is given by the integral over the merger history, based on the fraction of galaxies merging, and the likely time-scale for mergers (e.g., Conselice et al.

2003; Conselice 2009; Bluck et al. 2009; 2012). We carry out this integration using the observed merger history and time-scale for mergers (e.g., Bluck et al. 2009; 2012). When we do this calculation over our integral of time between $z = 3$ and $z = 1.5$ (see §4.3) we find that the total amount of stellar mass added by the merger process is, as a ratio of the initial stellar mass, $M_{*,M}(t)/M_*(0) = 0.54 \pm 0.23$.

This implies that the merger process, through both minor and major mergers, increase the stellar mass of selected galaxies by $\sim 50\%$ during the interval $z = 1.5 - 3$ (see Bluck et al. 2012 for details). By making assumptions about the gas content of these galaxies, based on the results in §3.1 we can then calculate how much gas is added over time due to these mergers. Furthermore, we can test whether the inferred amount of gas brought in with these mergers is enough to fuel the star formation we see in these systems during the epoch $1.5 < z < 3$.

4 COLD GAS ACCRETION

4.1 Formulation of Problem

A galaxy has several mass components that interlink with each other. These are the stellar mass (M_*), gas mass (M_g) and dark matter mass (M_{DM}). For the purposes of this paper we consider that the gas mass is cold. Although hot gas is present within galaxies at least in the local universe, the cooling time for these galaxies is very long and negligible for galaxies with masses similar to the ones we examine in this paper.

The total mass (M_{tot}) of a galaxy can then be written as:

$$M_{\text{tot}} = M_* + M_g + M_{DM} \quad (2)$$

where these terms are all expressible as a function of time. We first calculate using these terms the amount of stellar mass within a galaxy as a function of time $M_*(t)$. As the stellar mass in a galaxy will not significantly decrease, the value of M_* can in general only increase. This increase can occur through the accretion of outside material from mergers ($M_{*,M}(t)$), and through star formation. We write the increase due to star formation as $\langle \psi \rangle \delta t$, where $\langle \psi \rangle$ is the average star formation rate within the galaxy between an amount of time δt (§3.2).

We then write the change of stellar mass as a function of time, $M_*(t)$, as

$$M_*(t) = M_*(0) + M_{*,M}(t) + \langle \psi \rangle \delta t, \quad (3)$$

where $M_*(0)$ is the initial galaxy stellar mass, and $\delta t = t - t_0$. We can further express how the cold gas mass (M_g) changes in a similar way, although the cold gas mass can increase or decrease with time depending on the star formation and gas accretion rate.

$$M_g(t) = M_g(0) + M_{g,M}(t) + M_{g,A}(t) - \langle \psi \rangle \delta t \quad (4)$$

where in this case we have a term for the amount of cold gas brought in from mergers, $M_{g,M}(t)$, the amount from accretion of gas without other galaxies¹, or cold gas accretion,

¹ Note that this is not strictly true, as this gas in principle could arise from extreme minor mergers, those with mass ratios

$M_{g,A}(t)$. Furthermore the star formation ongoing within this fiducial system will lower the amount of cold gas over time by the amount $-\langle \psi \rangle \delta t$. We furthermore do not consider in these equations that some stellar mass created is later lost through stellar evolution processes in SN, nor do we consider the loss of gas through outflows which can be significant at these redshifts (e.g., Steidel et al. 2010; Faucher-Giguere et al. 2011). However, both of these effects would act to ultimately only increase the amount of gas accretion necessary.

One of the observations of our sample which we described in §3.1 is that the gas mass fraction, M_g/M_* is roughly constant over the interval $1.5 < z < 3$ (e.g., Erb et al. 2006; Genzel et al. 2009). In this case, we can write

$$\frac{M_g(t)}{M_*(t)} \sim \frac{M_g(0)}{M_*(0)}, \quad (5)$$

which is true in the redshift range we examine. Note that by using this condition the actual value of the gas to stellar mass ratios is immaterial for the following derivation. Thus, if we use a different relation between star formation density and gas density we would obtain the same results for the basic equations, although the final numerical result may differ (§4.3). We later examine how our net results would change if there was an evolution such that the gas mass density declined at lower redshifts (§4.3).

Using this measurement, we then write the amount of gas mass at a later time t , $M_g(t)$ by using equation 5. We then expressing the stellar mass evolution with time by using equation 3 to replace $M_*(t)$ from equation 5 to obtain

$$M_g(t) = M_g(0) \times \left(1 + \frac{M_{*,M}(t)}{M_*(0)} + \frac{\langle \psi \rangle \delta t}{M_*(0)} \right), \quad (6)$$

where the gas mass evolution is expressed in terms of the initial gas mass and as a function of how much relative mass is added to a galaxy over time due to the increase from star formation and the increase from mergers. These are much easier to determine than the corresponding absolute amounts (§3.2).

Therefore using equation (6), and the results presented in §3.2, we can write the total gas mass after a time δt with respect to the initial gas mass, $M_g(0)$ as

$$M_g(t) \sim (2.64 \pm 0.25) \times M_g(0), \quad (7)$$

such that the total gas mass within our galaxies at $z \sim 1.5$ must be on average ~ 2.64 times larger than the gas mass at the start of our redshift epoch near $z \sim 3$ due to the increase in stellar mass.

If we then equate this to equation (4) we can calculate that the accreted (or extra) gas mass is given by:

$$M_{g,A}(t) = (1.64 \pm 0.21) \times M_g(0) + \langle \psi \rangle \delta t - M_{g,M}(t). \quad (8)$$

if we divide this equation by the average initial stellar mass $M_*(0)$ we get:

$$\frac{M_{g,A}(t)}{M_*(0)} = \frac{(1.64 \pm 0.21) \times M_g(0)}{M_*(0)} + \frac{\langle \psi \rangle \delta t}{M_*(0)} - \frac{M_{g,M}(t)}{M_*(0)}. \quad (9)$$

which are less to 1:100 and which we are not sensitive to in our observations (Bluck et al. 2012). However, the total amount of gas needed implies that these extreme minor mergers would vastly outnumber the visible minor mergers at a level much higher than any reasonable extrapolation.

Therefore by knowing the initial average gas mass fraction, the fraction of stellar mass increase in the form of stars, and the gas mass fraction brought in through merging, we can determine the amount of gas mass, relative to our average galaxy's initial stellar mass, brought in through 'pure' accretion events, i.e., not gas brought in with merging galaxies.

4.2 Gas Accretion Mass Fraction

As we discuss in §3.1 we find that the initial gas mass fraction at $z = 3$ is $f_g = 0.17, \sigma = 0.19$, and that the fraction of stellar mass formed in star formation is $\langle \psi \rangle \delta t/M_*(0) = 1.1 \pm 0.13$, and the amount added from mergers is $M_{*,M}/M_*(0) = 0.54 \pm 0.23$. The most difficult of these values to determine is the ratio of the cold gas mass brought in from mergers to the total amount of initial stellar mass ($M_{g,M}(t)/M_*(0)$). However, we are able to make some measurement of this based on the amount of mass accreted from mergers ($M_{g,M}$) and the mass weighted gas mass fraction for these systems f_g . This gas contribution from the minor mergers is our key new measurement that allows us to later constrain how much gas is coming from the intergalactic medium to form galaxies.

To do this, we first examine the amount of stellar mass added due to the major and minor merger process. As detailed in Bluck et al. (2012) the merger fraction can be parameterized as a function of both stellar mass and redshift. Bluck et al. (2012) find that at $2.3 < z < 3$ the merger fraction dependence on mass stellar for galaxies more massive than $M_* > 10^{11} M_\odot$ is given by:

$$f_m(M_*) = (0.28 + / - 0.17) \times \delta \log(M_*)^{0.91 + / - 0.35} \quad (10)$$

and at $1.7 < z < 2.3$ we find a merger fraction dependence on mass range for massive galaxies of:

$$f_m(M_*) = (0.12 + / - 0.09) \times \delta \log(M_*)^{1.24 + / - 0.37}. \quad (11)$$

The total amount of stellar mass accreted is then a double integral over the redshift range of interest and over the stellar masses which we probe, which for the GNS is sensitive down to $M_* = 10^{9.5} M_\odot$ can be written as,

$$M_{*,M} = \int_{z_1}^{z_2} \int_{M_1}^{M_2} M_* \times \frac{f_m(z, M_*)}{\tau_m} dM_* dz. \quad (12)$$

Where τ_m is the merger time-scale, which likely depends on the stellar mass of the merging pair (Bluck et al. 2012). Our integration as mentioned in §3.2, gives a value of $M_{*,M}/M_*(0) = 0.54 \pm 0.23$. We integrate the amount of gas mass added in a similar way, through understanding what the ratio of stellar to gas mass is based on the data shown in Figure 2. This allows us to compute what the total amount of gas and the total amount of stellar mass accreted from these minor mergers is. We show in Figure 5 the relative amounts of gaseous and stellar mass as a function of the stellar mass of the merging galaxy. This shows that the contribution of stellar mass to an average massive galaxy in our sample from merging systems is highest around $M_* = 10^{10.8} M_\odot$ and declines at lower and higher masses. The gas mass accreted however is quite low for the highest mass galaxies, but increases at lower masses and stays relatively constant at values $M_* < 10^{10.5} M_\odot$.

Using this, we calculate how much gas mass is brought

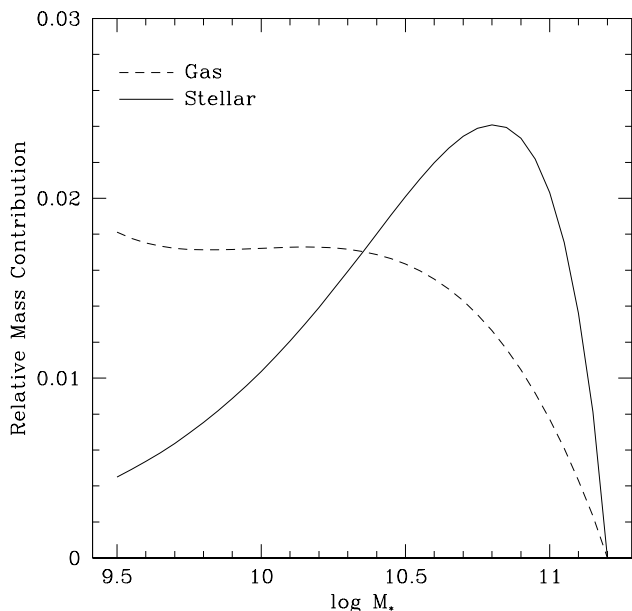


Figure 5. The relative amount of gaseous and stellar matter accreted from mergers of various masses between redshifts $1.5 < z < 3$. The x-axis is the stellar mass of galaxies merging with our typical average galaxy from our sample with $M_* = 10^{11.2} M_\odot$. The y-axis shows the relative contribution to the total for galaxies at masses separated by 0.05 dex. The solid line shows the stellar mass contribution and the dashed line the gaseous contribution.

into our galaxies due to these minor mergers. We calculate that the average stellar mass weighted gas mass fraction is $f_g \sim 1.03$ down to $M_* = 10^{9.5} M_\odot$. From this, we calculate $M_{g,M}/M_*(0) = M_{g,M}/M_*(0) \times f_g = 0.55 \pm 0.23$.

We can then use the above results and equation (9) to calculate the amount of gas accreted as a fraction of the initial stellar mass. Putting these together, we conclude that $M_{g,A}/M_*(0) = 0.83 \pm 0.37$. (13)

What this implies is that a roughly constant gas mass fraction seen in the observations of these distant galaxies (§3.1) reveals that on order the entire initial stellar mass of a massive galaxy is added over time outside of mergers to form stars during $1.5 < z < 3$. This equates to an absolute amount of gas accreted as $(1.8 \pm 0.8) \times 10^{11} M_\odot$ over 2.16 Gyr, or at an average rate of gas accretion of

$$\frac{dM_{g,A}(t)}{dt} = \dot{M}_{g,A} = (83 \pm 36) M_\odot \text{ yr}^{-1}, \quad (14)$$

needed to produce the star formation we observe. In the next section we evaluate the uncertainties within this measurement and in the section after give the implications of this result.

4.3 Uncertainties

There are systematic issues that could affect these results, some of which we examine in this section. One of these is that the star formation density-gas density relation (Schmidt-Kennicutt law) may evolve (e.g., Daddi et al.

2010). Since starbursts are more efficient, the initial gas mass could in principle be lower than what we are measuring. If the normal Schmidt-Kennicutt law then applied for the lower redshift galaxies in our sample the net result would be an *increase* in the gas mass to stellar mass ratio and equation 5 no longer strictly holds. Likewise, it may be possible that we are measuring the gas masses incorrectly too low at our highest redshift point for some reason and that there is actually a decrease with time in the gas mass fraction. We examine both of these scenarios quantitatively by considering how our relations would change if we use a gas mass density relation of the form:

$$\frac{M_g(t)}{M_*(t)} \sim \kappa \times \frac{M_g(0)}{M_*(0)}, \quad (15)$$

where κ is the relative change in the ratio between the gas to stellar mass at some lower redshift than at the initial time at $z \sim 3$. In this case, the relative gas mass accretion can be written as:

$$\frac{M_{g,A}(t)}{M_*(0)} = \kappa \times (2.64 \pm 0.26) \times \frac{M_g(0)}{M_*(0)} + \frac{\langle \psi \rangle \delta t}{M_*(0)} - \frac{M_{g,M}(t)}{M_*(0)}. \quad (16)$$

When using this equation with the value of $\kappa = 0.5$, where the gas mass fraction has dropped by a half, we find that the gas accretion mass fraction drops to $M_{g,A}/M_* = 0.78 \pm 0.37$. If we take the limiting case where all of the gas is exhausted from $z = 3$ to $z = 1.5$, where $\kappa = 0$, we would find a lower limit accreted gas mass fraction of $M_{g,A}/M_* = 0.56 \pm 0.37$. In general, if the gas mass fraction decreases with time, with perhaps an evolving form of the relation between gas mass density and star formation rate density, this would result in a slightly lowered derived gas mass accretion. For the more likely case of less efficient star forming systems over time, the net gas mass fraction would increase even more than our initial calculation, given that in this case $\kappa > 1$. However, most of the constraint on this measurement comes from the fact that there is a high ongoing star formation rate during this epoch, and the gas to fuel this star formation is not initially present within the galaxy, nor carried in through mergers.

If we directly consider the more efficient Schmidt-Kennicutt law, as proposed by Daddi et al. (2010) for star bursting galaxies to apply throughout our redshift range, we would then have a lower gas mass fraction at both the start and the end of our evolution. As above, we would still have to account for the star formation present within these systems, and this is the driving observation behind our calculation of a high gas mass accretion rate. However it is important to note that our galaxies are in the regime where they follow the standard law (Daddi et al. 2010), where the more efficient starburst are for sub-mm and ULIRG galaxies.

One remaining issue is that our star formation rates maybe too high, however, others have found very similar star formation rates or higher, for similar galaxies (e.g., Daddi et al. 2007). The star formation rates we measure are consistent in the ultraviolet and using *Herschel* far-infrared imaging (Hilton et al. 2012), and if anything we are at the lower end of the various star formation measurements (Bauer et al. 2011).

4.4 Implications

We present in this paper an analysis of the amount of cold gas mass which is likely accreted into massive galaxies with stellar masses $M_* > 10^{11} M_\odot$ at $1.5 < z < 3$. This amount of accreted gas is necessary to account for the observed star formation rate between redshifts $1.5 < z < 3$, which cannot be accounted for by gas brought in through minor+major mergers (Bluck et al. 2012). Our overall result is that we find a basic accretion rate of $\dot{M}_{g,A} = (83 \pm 36) M_\odot \text{ yr}^{-1}$ of cold gas needed from the IGM to account for this star formation.

Papovich et al. (2011) recently published a measurement of the total gas accretion rate at similar redshifts, which includes all methods that bring in gas. They were not able to distinguish between the gas brought in through mergers, and that brought in through gas accretion. Their results are similar to ours, finding a higher accretion rate, but that the total accretion is similar to what we find here, or slightly higher. We note that we are only able to probe mergers for massive galaxies down to $M_* = 10^{9.5} M_\odot$, and it is possible that the gas accretion we find originates from galaxies with stellar masses lower than this limit. Furthermore, we are not able to say whether the accreted gas originates in clumps into the galaxy or in a smooth continuous mode. Our result is an integrated average over the time-spanned by redshifts $1.5 < z < 3$.

There are several implications from these results. The first is that what we actually measure is the amount of cold gas accreted which is turned into stars. Because of the significant amount of outflows in galaxies, particularly those with star formation rates similar to ours, a significant fraction of all accreted gas is removed from the galaxy by these winds (e.g., Dekel et al. 2009; Dave et al. 2011). The result of these outflows, is that the amount of gas actually accreted is the combination of the outflowing gas as well as the gas used in star formation. This in principle could easily double the amount of gas mass needed to be accreted from the IGM (e.g., Faucher-Giguere et al. 2011). The ultimate morphologies of these galaxies in the local universe is also likely to be disk in some way, and would produce galaxies without large bulges as is found in merger remnants. This result also explains how massive galaxies in the very local universe, within 8 Mpc, can have almost no bulges (e.g., Kormendy et al. 2010), as gas accretion is the dominant process for their formation. Gas accretion is also one way to solve the G-dwarf problem of having too many metal rich stars in the solar neighbourhood (e.g., Larson et al. 1974), and may relate to the gas accretion we see in our own galaxy (Blitz et al. 1999).

Overall our result of finding an accretion rate of gas of $\dot{M}_{g,A} = (83 \pm 36) M_\odot \text{ yr}^{-1}$ for the most massive galaxies at $1.5 < z < 3$ is roughly consistent with theoretical observations which predict a similar amount of gas accretion (Murali et al. 2002; van den Bosch 2002; Keres et al. 2005; Dekel et al. 2009; McBride et al. 2009). Early simulations by Murali et al. (2002) predict a gas accretion rate of $\dot{M}_{g,A} \sim 40 M_\odot \text{ yr}^{-1}$, while more recent work suggests higher rates of $\dot{M}_{g,A} \sim 100 M_\odot \text{ yr}^{-1}$ (e.g., Dekel et al. 2009a,b; Faucher-Giguere et al. 2011). Our results are in general agreement with these models, although we are only examining a narrow redshift and stellar mass interval within this paper.

Our results also reveal that amongst the material put

into place in massive galaxies, the gas accretion accounts for $61 \pm 21\%$ of the stellar matter added to galaxies from $1.5 < z < 3$. Mergers account for the remainder of the 39% of the mass added to galaxies over this epoch, with 1/3 of this minor mergers and 2/3 of this major mergers (Bluck et al. 2012). Overall this implies that gas accretion into massive galaxies at early epochs is a major formation method, and dominates over mergers as a formation process.

Our results from this work, and previous papers examining the issue of stellar mass formation modes (e.g., Conselice 2006; Bluck et al. 2012) is similar to what is predicted in several studies using N-body simulations. This includes Genel et al. (2010), who find through simulations that about 60% of the halo mass in galaxies is put into place through merging, with at least 40% of the mass coming from accretion. We also find about a 50-50 ratio of these two formation modes. Furthermore, using hydrodynamical models, Murali et al. (2002) find that for galaxies brighter than about a fourth of L^* , the characteristic luminosity, gas accretion dominates over merging as a mechanism, whereby gas accretion, accounting for $\sim 75\%$ of the stellar mass build up at $z \sim 2$. While others, e.g., Stewart et al. (2008) find that over half of the mass in galaxies is formed in mergers, while others such as Angulo & White (2010) find that nearly all the mass in galaxies is put into place via mergers. These last few suggest that mergers are the dominant process, while we find that gas accretion is more important. However, our investigation is only for the most massive galaxies, and this may not be representative of typical galaxies at these redshifts. Future studies will have to probe deeper to obtain the merger history for lower mass systems to carry out similar calculations as these and probe this evolution in different environments.

5 SUMMARY

We present in this paper a study of the cold gas mass densities for massive galaxies with $M_* > 10^{11} M_\odot$ at redshifts of $1.5 < z < 3$. While we do not directly detect the accretion of gas within our galaxies, we are able to make a circumstantial finding for its existence. Our conclusions are as follows:

I. Utilizing our measured star formation rates and galaxy sizes we find a roughly constant cold gas mass to stellar mass fraction for this sample across the redshift range of $1.5 < z < 3$.

II. We utilize the star forming and merging properties of these galaxies from previous work in Bauer et al. (2011) and Bluck et al. (2012) to measure the mass budget of our sample of massive galaxies, finding that $\dot{M}_{g,A} = (83 \pm 36) M_\odot \text{ yr}^{-1}$ of gas is needed to sustain the star formation rate outside of gas brought in via mergers.

III. We derive based on these values that cold gas accretion from the intergalactic medium, or alternatively very minor galaxy mergers with mass ratios lower than 1/100, accounts for $61 \pm 21\%$ of the baryonic matter added to galaxies from $1.5 < z < 3$.

This amount of gas mass added is larger than the amount of material added due to the merger process (both minor and major) (e.g., Conselice 2006; Bluck et al. 2012) and is largely in agreement with models which predict on the order of $100\text{--}200 M_\odot \text{ yr}^{-1}$ added from cold gas accretion (e.g., Dekel et al. 2009). Gas accretion is therefore the

major method for building up the stellar masses of massive galaxies between redshifts $1.5 < z < 3$. The remainder of the formation is due to merging.

Further work with e.g., the CANDELS survey will allow us to carry out this measurement for lower mass galaxies where the mode of formation could be significantly different than the more massive systems (e.g., Dekel et al. 2009). Also, we are examining in this paper massive systems in the last throws of their formation at $z < 3$. Investigating the ratio of formation due to mergers and gas accretion at $z > 3$ will reveal how the first epochs of these massive galaxies were formed. This however will require observations from JWST and the ELTs.

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